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Original Article

Quantitative assessment of circumduction, hip hiking, and forefoot contact gait using Lissajous figures

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ABSTRACT
Itoh N, Kagaya H, Saitoh E, Ohtsuka K, Yamada J, Tanikawa H, Tanabe S, Itoh N, Aoki T, Kanada Y. Quantitative assessment of circumduction, hip hiking, and forefoot contact gait using Lissajous figures. Jpn J Compr Rehabil Sci 2012; 3: 78−84.
Objective: To quantitatively assess gait abnormalities using Lissajous figures obtained from three-dimensional motion analysis of treadmill gait, with the goal of applying the findings to the treatment of gait disorders.
Methods: Thirty-nine healthy subjects and 30 hemiplegic patients were studied. Treadmill gait analysis was conducted using a three-dimensional motion analysis system. Using the Lissajous figures obtained from the gait analysis, quantitative indexes were developed for three gait abnormalities: circumduction, hip hiking, and forefoot contact. The indexes were validated through comparison with observational assessment by physiotherapists with expertise in gait analysis.
Results: The values obtained for all the indexes were significantly higher in hemiplegic patients compared to healthy subjects ($p < 0.001$). Correlation analysis was conducted between the index values and observational scores for each gait abnormality, yielding Spearman's rank correlation coefficients of −0.82 for circumduction, −0.64 for hip hiking, and −0.84 for forefoot contact ($p < 0.001$).
Conclusion: We successfully developed objective quantitative indexes for gait abnormalities, which were not influenced by rater bias.
Key words: treadmill, gait analysis, abnormal gait, Lissajous figures

Introduction

Among the various approaches to gait analysis, observational assessment is the most commonly used method in the clinical setting. Observational gait analysis has the advantage of being quick and easy to use. However, since the assessment of abnormality and severity depends on the subjective judgment of the rater, reliability is an issue. In fact, the reliability of observational gait analysis is reported to vary greatly depending on the disease studied, assessment content, and experience of the raters [1−6]. On the other hand, gait analysis using a three-dimensional motion analysis system is objective, and is used not only in research but also in the clinical setting [7]. However, as it is difficult for non-experts to interpret the results obtained from motion analysis, this method is not widely used as a routine clinical test. We have developed a method in which treadmill gait analysis is performed and the motion of the markers is expressed in Lissajous figures, which are easily understandable even by non-experts. A Lissajous figure is a curve traced out by a point undergoing two independent simple harmonic motions at right angles to each other. Use of the treadmill for gait analysis has various merits: (1) the subject walks within the same space, eliminating the need for a large area; (2) walking speed can be controlled; (3) multiple steps can be analyzed easily; and (4) use of a suspension and handrail is possible, thus allowing assessment of patients with poor gait capability.

The purpose of the present study was to use Lissajous

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figures obtained from three-dimensional motion analysis of treadmill gait to develop quantitative indexes for the typical gait abnormalities in hemiplegic patients (circumduction, hip hiking, and forefoot contact), and to examine the validity of the indexes through comparison with observational assessments by physiotherapists with expertise in gait analysis.

Methods

Thirty-nine healthy subjects and 30 hemiplegic patients were studied. The healthy subjects were 28 males and 11 females aged 30 ± 5 years, 167.3 ± 8.5 cm in height and 62.1 ± 10.7 kg in weight (mean ± standard deviation). The demographic and clinical profile of the hemiplegic patients is shown in Table 1.

This study was approved by the ethical committee of our institution. Written informed consent was obtained from all subjects after they were given a detailed explanation of the purpose and contents of the study both orally and in writing. Following an explanation of the study content, informed consent was also obtained from the four physiotherapists (clinical experience 15.8 years on average, ranging from 8 to 34 years) who conducted observational gait analysis.

The KinemaTracer® three-dimensional motion analysis system (Kissei Comtec Co., Ltd., Matsumoto, Japan) was used in this study. The KinemaTracer® is composed of a computer for recording and analysis, together with four CCD cameras that were installed around the treadmill. Since the subjects were not familiar with walking on the treadmill, they practiced in advance. After an adequate amount of practice, the three-dimensional coordinates of the body markers were determined (X: left/right, Y: anterior/posterior, Z: superior/inferior). A total of ten markers (30 mm in diameter) were placed bilaterally on the acromia, hip joint (one-third distance from the great trochanter on a line joining the anterior superior iliac spine and great trochanter), knee joints (midpoint of the anteroposterior diameter of the lateral femoral epicondyle), ankle joints (lateral malleolus), and toes (5th metatarsal head). Treadmill speed was set at 4 km/h for healthy subjects, and at the subjectively comfortable gait speed or 70 % of that speed for hemiplegic patients. The subjectively comfortable gait speed was the mean speed of two determinations for a 10-m walk. Hemiplegic patients were allowed to use a handrail or brace. Video was recorded at a sampling frequency of 60 Hz and a measuring time of 20 s. At the same time, two video cameras (Handycam HDR-FX1, Sony) were set at the lateral and posterior sides of the affected side to record treadmill gait at a sampling frequency of 30 Hz, and the videos were used for observational gait analysis.

The definitions for the studied gait abnormalities – circumduction, hip hiking, and forefoot contact – are shown in Table 2 [8, 9]. Measurements for the indexes for these gait abnormalities were as follows. The index for circumduction was measured as the difference in distance between the lateral-most X coordinate of the ankle joint marker during 25–75 % of the swing phase and the medial-most X coordinate during 25–75 % of the stance phase (Figure 1). The index for hip hiking was obtained from the difference between the maximum value of the Z coordinate of the hip joint marker during the swing phase and the Z coordinate of the contralateral hip joint marker at the same time, corrected for the mean left-right difference of the Z coordinate during the double support phase (Figure 2). The index for forefoot contact was obtained from the difference in distance between the Z coordinate of the ankle joint marker and the Z coordinate of the toe marker at initial contact, minus the difference in distance between the Z coordinates of the ankle joint

Table 1. Demographic and clinical profile of hemiplegic patients.

Age	58 ± 14 (21–87) years
Height	164.1 ± 8.6 (140–176) cm
Weight	60.6 ± 9.4 (38–78) kg
Gender	24 males, 6 females
Diagnosis	Cerebral infarction, 17; Brain hemorrhage, 11; Subarachnoid hemorrhage, 1; Traumatic brain injury, 1
Affected side	Right, 18; left, 12
Time from onset	1,072 ± 1,485 (21–6,026) days
Lower limb Brs[1]	Stage Ⅰ, 1; Stage Ⅱ, 0; Stage Ⅲ, 4; Stage Ⅳ, 15; Stage Ⅴ, 9; Stage Ⅵ, 1
Gait FIM[2]	Level 4, 1; Level 5, 10; Level 6, 18; Level 7, 1
Cane use	Yes, 24; No, 6
Brace use	Yes, 19; No, 11

Data on age, height, weight and time from onset is expressed as the mean ± standard deviation (range).
[1] Brs, Brunnstrom Stage; [2] FIM, Functional Independence Measure.

Table 2. Definition of various gait abnormalities.

1. Circumduction

   Lower extremity of the affected side shows hip joint abduction and lateral rotation during initial swing to mid-swing, and hip joint adduction and medial rotation during mid-swing to terminal swing, following a semicircular trajectory. Severity is assessed by the amount of lateral displacement of the foot on the affected side during the swing phase.

2. Hip hiking

   The pelvis on the affected side is raised during pre-swing to mid-swing, associated with shortening of the trunk on the affected side. Severity is assessed by the amount of vertical displacement of the pelvis on the affected side from pre-swing to mid-swing.

3. Forefoot contact

   At initial contact, the forefoot on the affected side is the first to make contact, regardless of walking brace use. Severity is assessed by the magnitude of the plantarflexion angle of the ankle joint at initial contact.

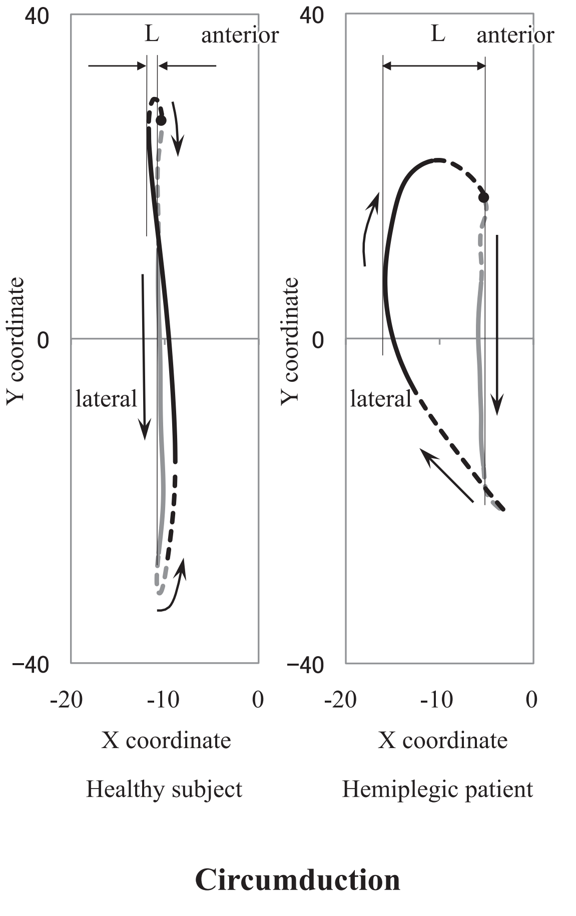
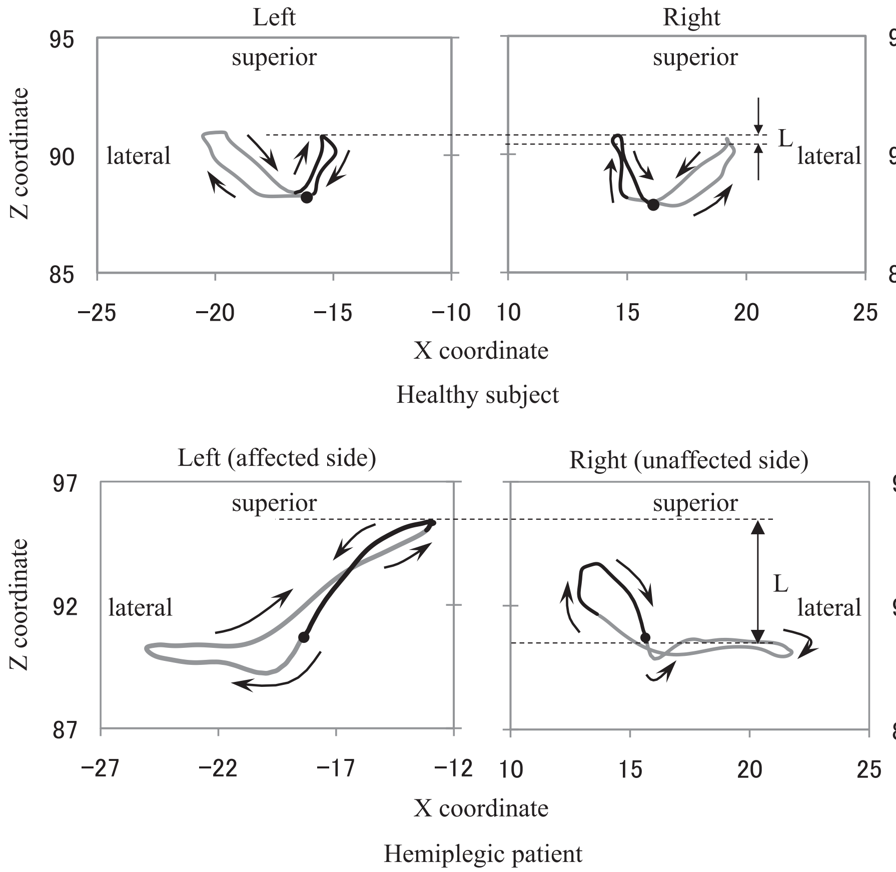


Figure 1. Lissajous figures used to measure the index for circumduction.
Lissajous figures at the horizontal plane of the left ankle joint marker in a healthy subject and in a patient with left hemiplegia are shown. The coordinates are X: left/right (+: right, −: left) and Y: anterior/posterior (+: anterior, −: posterior). The gray line denotes the stance phase, and the black line denotes the swing phase. The interval between 0−25 % of the stance phase and 75−100 % of the swing phase is shown by the dotted line. The closed circle indicates initial contact, and L is the index value.

marker and toe marker during standing (Figure 3). The normal range of each index was defined as the mean ± two standard deviations of the values obtained from healthy subjects.

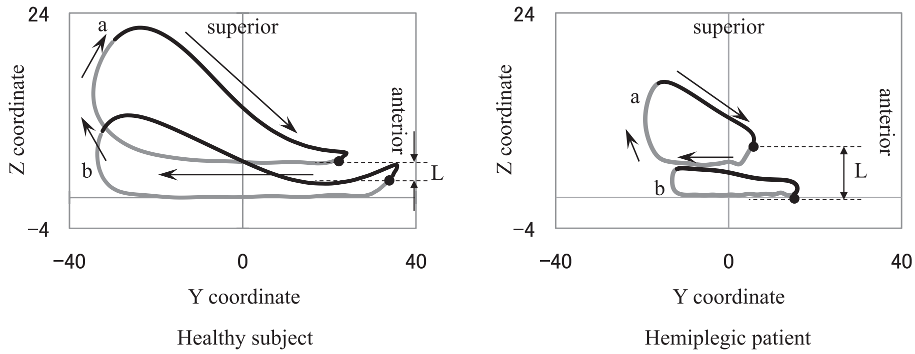
Observational assessment of gait abnormalities was conducted by four physiotherapists with expertise in gait analysis. The raters observed the videos of the treadmill gait of each subject and scored the severity of each gait abnormality on a five-point scale (Table 3). Before scoring, the raters standardized the definitions for the gait abnormalities. The time of observation of the videos taken from the affected side and posterior side was 15 s for each direction, totally 30 s. For scoring, the raters observed the videos of all the subjects at once, and then observed each subject individually. Consultation among the physiotherapists was not allowed. The median score of the four physiotherapists was used as the final result of assessment of each gait abnormality. To verify the inter-rater reliability of scoring, we calculated Cohen's κ coefficient and the weighted κ coefficient, assigning a discrepancy of one rank as 50 % agreement.

Data is expressed as the mean ± standard deviation. Comparison of the index values for each gait abnormality between healthy subjects and hemiplegic patients was conducted using the Mann-Whitney U-test. To examine the validity of the index for each gait abnormality, a correlation analysis was conducted between the index value and observational score, and Spearman's rank correlation coefficient was calculated. Statistical analyses were performed using PASW Statistics 18.0 (SPSS Inc., Chicago, USA). A p value of less than 0.05 was considered statistically different.



Hip hiking

Figure 2. Lissajous figures used to measure the index for hip hiking.
Lissajous figures at the frontal plane of the bilateral hip joint markers in a healthy subject and in a patient with left hemiplegia are shown. The coordinates are X: left/right (+: right, −: left) and Z: superior/inferior (+: superior; −: inferior). The gray line denotes the stance phase, and the black line denotes the swing phase. The closed circle indicates initial contact, and L is the index value.



Forefoot contact

Figure 3. Lissajous figures used to measure the index for forefoot contact.
Lissajous figures at the sagittal plane of the right ankle joint marker (a) and right toe marker (b) in a healthy subject and in a patient with right hemiplegia are shown. The coordinates are Y: anterior/posterior (+: anterior, −: posterior) and Z: superior/inferior (+: superior; −: inferior). The gray line denotes the stance phase, and the black line denotes the swing phase. The closed circle indicates initial contact, and L is the index value.

Table 3. Scores for each gait abnormality.

Circumduction / Hip hiking	Forefoot contact
5: No abnormality	5: Heel contact – adequate dorsiflexion
4: Minimal abnormality	4: Foot contact – inadequate dorsiflexion
3: Mild abnormality	3: Mild forefoot contact
2: Moderate abnormality	2: Moderate forefoot contact
1: Severe abnormality	1: Severe forefoot contact

Results

1. Index values of gait abnormalities

The index values (mean ± standard deviation) for the gait abnormalities were as follows. Index values for circumduction were 0.78 ± 1.09 cm in healthy subjects and 2.96 ± 2.75 cm in hemiplegic patients. Index values for hip hiking were 0.26 ± 0.53 cm in healthy subjects and 1.73 ± 1.08 cm in hemiplegic patients. Index values for forefoot contact were −2.79 ± 0.64 cm in healthy subjects and −0.12 ± 1.31 cm in hemiplegic patients. For all indexes, the values were significantly higher in hemiplegic patients compared with healthy subjects ($p < 0.001$). The normal ranges (mean ± two standard deviations) were −1.40 to +2.96 cm for circumduction, −0.80 to +1.32 cm for hip hiking, and −4.07 to −1.51 cm for forefoot contact.

2. Validity of indexes for gait abnormalities

The relationship between observational score and index value for each gait abnormality is shown in Figure 4. In observational gait analysis, the number of hemiplegic patients rated as normal (score 5) was 19 for circumduction, 7 for hip hiking, and 2 for forefoot contact. In quantitative gait analysis, the number of hemiplegic patients with index values within the normal range was 17 for circumduction, 14 for hip hiking, and 4 for forefoot contact. The number of patients who were visually rated as normal and had index values within the normal range was 16 for circumduction, 6 for hip hiking, and 1 for forefoot contact. The number of patients who were visually rated as abnormal and had index values outside the normal range was 10 for circumduction, 15 for hip hiking, and 25 for forefoot contact. The correlation coefficients were −0.82 for circumduction, −0.64 for hip hiking, and −0.84 for forefoot contact. A significant correlation was observed in all the indexes of gait abnormalities ($p < 0.001$ for all).

The inter-rater reliability for observational assessment was examined. Cohen's κ coefficient (for full agreement) ranged from 0.20 to 0.45, and the weighted κ coefficient ranged from 0.31 to 0.58 (Table 4).

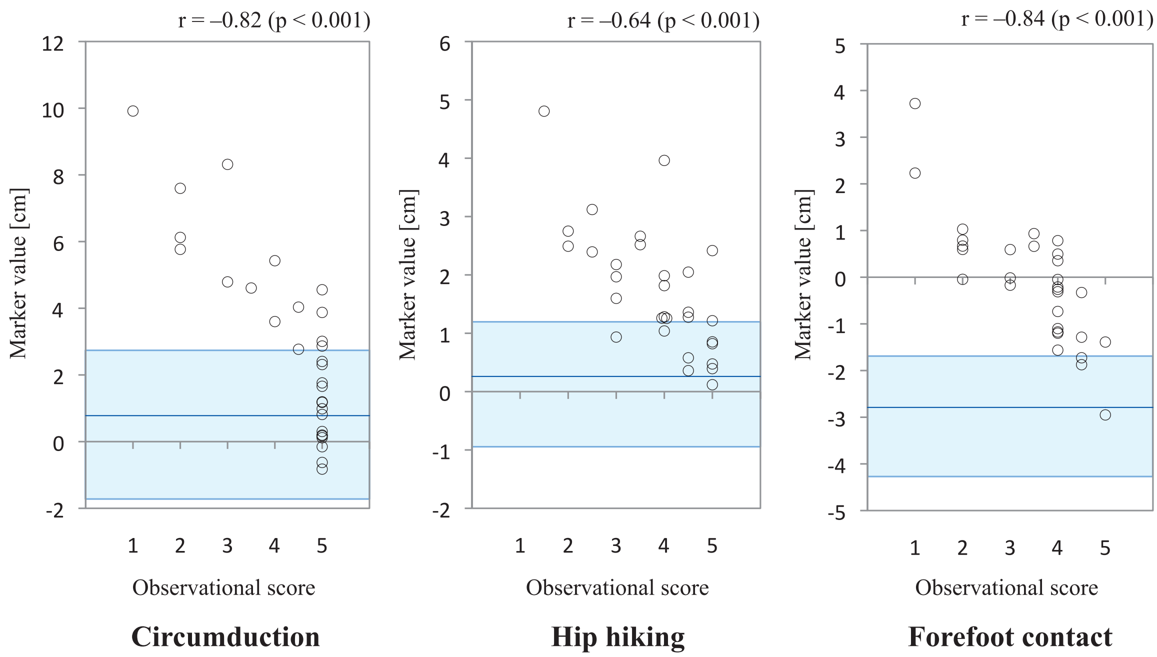


Figure 4. Relationship between observational score and marker value for each gait abnormality.
The blue horizontal line is the mean value obtained from healthy subjects, and the blue shaded area is the normal range. Open circles represent the data on hemiplegic patients.

Table 4. Inter-rater reliability of observational gait analysis.

	Cohen's κ coefficient	Weighted κ coefficient
Circumduction	0.45 (0.30–0.63)	0.52 (0.35–0.75)
Hip hiking	0.20 (0.02–0.29)	0.31 (0.10–0.45)
Forefoot contact	0.43 (0.31–0.57)	0.58 (0.48–0.67)

Data is expressed as the mean (range).

Discussion

Gait analysis using marker coordinates to produce a cyclogram was proposed by Bernstein in the 1960s [10]. However, body marker trajectories were rarely used as indexes for gait analysis until much later. In recent years, Hilder et al. [11] compared robot-assisted gait movement with treadmill gait movement of healthy subjects utilizing the movement trajectories of the hip joint, knee joint and ankle joint at the sagittal and frontal planes. Minetti et al. [12] used the three-dimensional trajectory of the body center to analyze gait and running. In the present study, we used the Lissajous figures obtained from anatomical locations characterizing gait abnormalities (circumduction, hip hiking, and forefoot contact) as indexes, and compared the results of quantitative analysis using these indexes with the scores from observational assessment by physiotherapists with expertise in gait analysis. Our results showed that all the index values were significantly larger in hemiplegic patients compared with healthy subjects, confirming that these indexes are useful for indicating gait abnormalities. In addition, in patients assessed by observational analysis as having gait abnormality (scores 1 to 4), almost all the index values were outside the normal ranges. Furthermore, a strong correlation was observed between the observational scores and the values of all three indexes, indicating that the indexes are valid for the assessment of gait abnormalities.

Conventional gait analysis using a three-dimensional motion analysis system quantifies time-distance factors such as stride time and length, or kinematic factors such as joint angle [13]. This data alone does not clearly convey a gait abnormality and is often difficult to understand for non-experts, which is the main problem of the analysis. On the other hand, in our novel method, the Lissajous figures of the markers depict the movement patterns, per se, of various gait abnormalities, and are used to quantitatively calculate the index values. Therefore, even non-experts can intuitively understand the motion analysis.

Conventional observational gait analysis is influenced by the experience of the raters. A manual or guide is necessary to ensure that the assessment is conducted with a high degree of accuracy [14], and a clear definition of the measurement standards will improve the inter-rater reliability [15]. In the present study, the raters were physiotherapists with expertise in gait analysis, and observational assessment was conducted after standardizing the definition of each gait abnormality. The κ coefficient can be interpreted as follows: inter-rater agreement is considered slight at 0.00–0.20, fair at 0.21–0.40, moderate at 0.41–0.60, substantial at 0.61–0.80, and almost perfect at 0.80–1.00 [16]. Eastlack et al. [2] reported that 54 physiotherapists assessed the gait of three patients with rheumatoid arthritis on a three-point scale, and the generalized κ coefficients ranged from 0.11 to 0.52. In a study by Keenan et al. [6], five podiatrists used a three-point scale to evaluate the gait of 14 adults with no history of orthopedic diseases, and reported poor inter-rater agreement (κ coefficient 0.19). In the present study, the inter-rater agreement was slight to moderate, and is not inferior to previous reports. To ensure the reliability of the observational gait analysis, we used the median score in the correlation analysis. A high correlation was obtained between the median score of observational assessment and the indexes using Lissajous figures, indicating that we have successfully developed quantitative indexes of gait abnormalities, which are more objective and not affected by rater bias.

In this study, hemiplegic patients were allowed to use a handrail and brace. However, neither device was used during measurements in healthy subjects, based on which the normal ranges were determined. This difference may have affected the present results, and further investigation is required.

In rehabilitation medicine, the use of objective and quantitative indexes in gait analysis is essential for refinement of gait training for individual patients. The introduction of gait analysis that can be used in the busy clinical setting, in a manner that is easily and intuitively understandable, would contribute to improved rehabilitation. Quantitative evaluation of other gait abnormalities will be attempted in the future.

References

1. McGinley JL, Goldie PA, Greenwood KM, Olney SJ. Accuracy and reliability of observational gait analysis data: judgments of push-off in gait after stroke. Phys Ther 2003; 83: 146–60.
2. Eastlack ME, Arvidson J, Snyder-Mackler L, Danoff JV, McGarvey CL. Inter-rater reliability of videotaped

observational gait-analysis assessments. Phys Ther 1991; 71: 465−72.
3. Hughes KA, Bell F. Visual assessment of hemiplegic gait following stroke: pilot study. Arch Phys Med Rehabil 1994; 75: 1100−7.
4. Brunnekreef JJ, van Uden CJ, van Moorsel S, Kooloos JG. Reliability of videotaped observational gait analysis in patients with orthopedic impairments. BMC Musculoskelet Disord 2005; 6: 17.
5. Krebs DE, Edelstein JE, Fishman S. Reliability of observational kinematic gait analysis. Phys Ther 1985; 65: 1027−33.
6. Keenan AM, Bach TM. Video assessment of rearfoot movements during walking: a reliability study. Arch Phys Med Rehabil 1996; 77: 651−5.
7. McGinley JL, Baker R, Wolfe R, Morris ME. The reliability of three-dimensional kinematic gait measurements: a systematic review. Gait Posture 2009; 29: 360−9.
8. Perry J. Pathological Gait. Gait Analysis: Normal and Pathological Function. Thorofare: NJ, SLACK; 1992, p. 169−347.
9. Kerrigan DC, Frates EP, Rogan S, Riley PO. Hip hiking and circumduction: quantitative definitions. Am J Phys Med Rehabil 2000; 79: 247−52.
10. Bernstein NA. The co-ordination and regulation of movement. London: Pergamon Press; 1967. p. 1−21.
11. Hidler J, Wisman W, Neckel N. Kinematic trajectories while walking within the Lokomat robotic gait-orthosis. Clin Biomech 2008; 23: 1251−9.
12. Minetti AE, Cisotti C, Mian OS. The mathematical description of the body centre of mass 3D path in human and animal locomotion. J Biomech 2011; 44: 1471−7.
13. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. J Orthop Res 1990; 8: 383−92.
14. Johnston MV, Keith RA, Hinderer SR. Measurement standards for interdisciplinary medical rehabilitation. Arch Phys Med Rehabil 1992; 73: S3−23.
15. Bernhardt J, Bate PJ, Matyas TA. Training novice clinicians improves observation accuracy of the upper extremity after stroke. Arch Phys Med Rehabil 2001; 82: 1611−8.
16. Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics 1977; 33: 159−174.